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The role of the transfer of nucleons in driving double charge exchange reactions

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Abstract. Transfer is an excellent tool to get insights into the short-range correlations on nucleons in a nuclear state. Within the context of direct reactions, the double charge exchange reactions have recently gained attention once their matrix elements might be associated with the double-beta decay rates. This class of reaction can occur from two completely distinctive mechanisms. They can take place by nucleons exchange or driven by mesons exchange between the projectile and target nuclei. Once the double charge exchange driven by multi-nucleon or mesons exchanges can compete with each other, it is crucial to analyze the contribution of the multi-nucleon transfer in this type of reaction to verify its relevance on the measured cross sections.

1. Introduction

One- and two nucleon transfer reactions are suitable tools to probe single-particle and pairing correlations in a nuclear state. Such reactions have extensively been studied in the last years [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16]. The theoretical prescriptions used to determine the angular distributions and integrated cross-sections in all of these studies provided a very good agreement with the experimental data. On the other hand, it was also relevant to verify the single- or two-particle features of the accessed nuclear states in the reactions related to the two-particle transfer. This was achieved by comparing the theoretical predictions for the transfer cross sections obtained from a sequential or simultaneous two-particle transfer process.

Nowadays, a great effort is being carried out to analyze the double charge exchange (DCE) reactions from both the experimental and theoretical points of view. The reason is that the matrix element of this kind of reaction may be associated with the inverse double-beta decay process [17, 18]. The main objective of many of these studies has been to provide precise information about the nuclear matrix element of the correlated DCE transition, which has common features of the one corresponding to the hypothetical neutrinoless double beta decay ($0\nu\beta\beta$) phenomenon. From this point of view, two correlated isovector mesons are exchanged by target and projectile in a single step action of the initial and final state nucleus-nucleus interaction. Moreover, as the form factor is based on the isovector component of the short-range nucleon-nucleon correlation, it can be linked to the nuclear response as the high-momentum neutrinoless double beta decay operator. The NURE[19] and NUMEN[20] projects were proposed to comprehensively study of the experimental data and theoretical predictions concerning the DCE process.

The meson driven DCE induced by heavy ions may compete with multi-nucleon transfer that connects the same initial and final nuclei between the target and projectile (called here as transfer-DCE). It is necessarily a multi-step process between the initial and final interaction states. Moreover, the nature of the form factors is built on the nucleon-nucleus mean-field perspective. The multi-nucleon transfer seeking of the DCE mechanisms is not directly connected to neutrino-less double beta decay studies. However, a careful study of the transfer-DCE is critical once it could be a relevant component of the measured DCE cross sections. Therefore, it is vital to know what is their contribution to the measured cross section and to look for experimental conditions where they can be minimized. Besides, the analysis of the transfer-DCE mechanisms can provide additional information upon the single-particle orbitals and nucleon-nucleon pairing correlations on the nuclear states involved in double beta decays. For this purpose, accessible experimental data are essential to study each transfer process appearing in the DCE reaction.

In the present work, we will study the possible contribution of the multi-nucleon transfer reaction to the DCE ^{116}Cd(^{20}Ne,^{20}O)^{116}Sn reaction, using the same methodology using to describe one- and two-particle transfer in recent works.

2. Results and discussion

From the multi-nucleon transfer point of view, the DCE reaction can occur by exchanging four nucleons between the projectile and target nuclei. In this context, two neutrons are transferred from the projectile to the target and two protons in the inverse direction. The appositive reaction is also possible. This means that the transfer-DCE can occur through transfer mechanisms of up to four steps, depending on whether two neutrons or two protons are transferred simultaneously or sequentially.

The analysis of the two-nucleon transfer reactions considering the coupled reaction channel (CRC) and distorted wave Born approximation (DWBA) approaches has recently been performed for the many systems, as for instance ^{18}O+^{12}C[21], ^{18}O+^{13}C[22], ^{18}O+^{16}O[1, 23], ^{18}O+^{28}Si[3], ^{18}O+^{64}Ni[24], ^{20}Ne+^{116}Cd[6] and ^{9}Be+^{7}Be[5]. Also, the one-particle transfer cross sections has been studied in the reactions ^{18}O+^{12}C[21], ^{18}O+^{16}O[2], ^{18}O+^{28}Si[2], ^{18}O+^{64}Ni[2], d+^{55}Mn[4], ^{18}O+^{40}Ca[9], ^{18}O+^{48}Ti[25] and ^{20}Ne+^{116}Cd[26]. Particularly, to analyze two-particle transfer reactions two different mechanisms are possible: *i*) both valence nucleons can be transferred simultaneously from the initial state to the final state; and *ii*) the two valence particles can be transferred one by one, passing through an intermediate partition. Moreover, the sequential two-particle transfer calculations are performed considering the two-step DWBA framework or coupled channel Born approximation (CCBA) in case couplings between the ground and inelastic states were explicitly included in the initial partition.

The independent coordinates scheme is used in the coupled reaction equations to determine the desired cross sections concerning the simultaneous two-particle transfer. In this context, a Woods-Saxon potentials are used to generate the single-particle wave function of each valence nucleon. Then a transformation of coordinates is performed to convert the independent coordinates of both valence nucleons into the center of mass coordinates of the two nucleons and the relative motion coordinate. This methodology for the simultaneous two-particle transfer has extensively been used in Refs.[3, 5, 6, 7, 10, 21, 22, 24]. The transfer calculations were performed by using the FRESCO code [27, 28] to solve the coupled reaction Schrödinger equations. The NUSHELLX [29] code was considered in the structure calculations to derive the one- and two-nucleon spectroscopic amplitudes.

In Fig. 1, we present some of these theoretical results obtained for the two-particle transfer angular distributions and even for the alpha-particle elastic-transfer process. Either in the transfer of one or two particles or even in multi-nucleon transfer calculations, the São Paulo potential was assumed in the real and imaginary parts of the optical potential in all the partitions. The theoretical predictions have described quite well the experimental data. Fig. 1(a) and (d) show the role played by the direct (full red line) and sequential (blue dashed line) two-particle transfer mechanisms in the ^{13}C(^{18}O,^{16}O$_{\rm g.s.}$)^{15}C$_{\rm g.s.}$ and ^{40}Ca(^{18}O,^{20}Ne$_{\rm g.s.}$)^{38}Ar$_{\rm g.s.}$, respectively. In both cases, the direct and sequential two-particle transfer mechanisms compete independently whether the two transferred particles are charged or not. Besides, Fig. 1(b) is shown experimental data and theoretical predictions for the two-neutron striping transfer in the ^{18}O+^{13}C collision, at 275 MeV bombarding energy, populating the two-correlated excitation mode with $E_x = 17.1 \pm 0.2$ MeV and identified as a Giant Pairing Vibration (GPV). The transfer calculation was performed considering the extreme cluster model. On the other hand, Fig. 1(c) illustrates a comparison between the experimental data and theoretical results concerning the alpha-particle stripping transfer for the ^{13}C(^{18}O,^{16}O$_{\rm g.s.}$)^{15}C$_{\rm g.s.}$ reaction. The alpha-particle spectroscopic amplitudes were derived considering the semi-microscopic algebraic cluster model [30]. The transfer result is represented by the full red curve (α-tr(1)). In addition, the alpha-particle transfer also was calculated by using the spectroscopic amplitudes from Ref. [31] in which the agreement between the experiment and result is quite good (α-tr(2)), despite the amplitudes to be reasonably different when compared to that one derived from the semi-microscopic algebraic cluster model (see Ref. [30] for details).

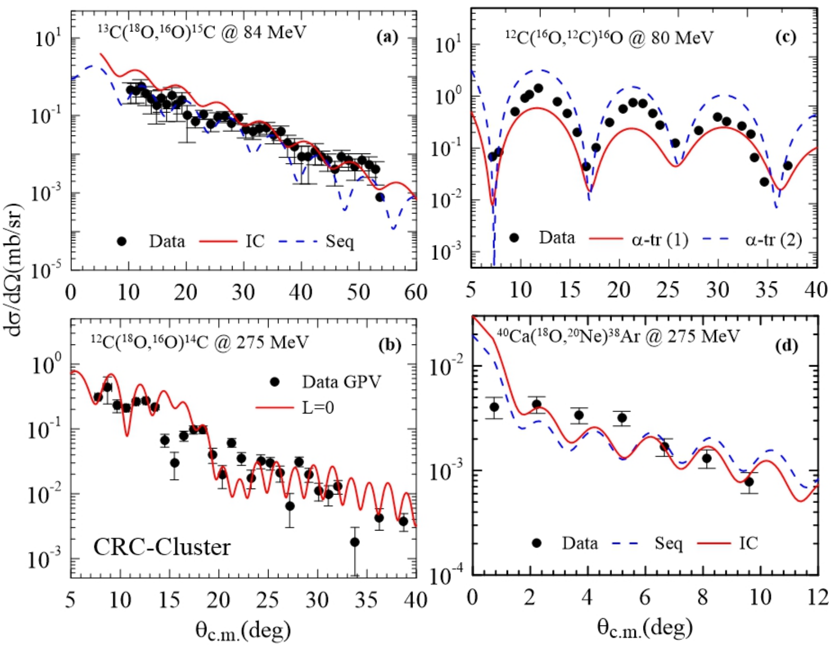

Figure 1. (color online) In panel (a), a comparison between theoretical and experimental angular distribution for the two-neutron stripping transfer in the ^{18}O+^{13}C collision is shown. Panel (b) shows the angular distribution for the two-neutron stripping reaction in the ^{18}O+^{12}C populating a Giant Pairing Vibration (GPV) state. In panels (c) and (d), a comparison between theoretical prediction and experiment is shown for the angular distributions concerning the transfer of one alpha particle and two protons, respectively. All the results are in quite an agreement with the experimental data.

From now, we will show some theoretical cross-sections results concerning the multi-nucleon transfer reactions for the ^{20}Ne+^{116}Cd collision at 306 MeV incident energy.

Fig. 2 illustrates the different possible reaction paths leading to the same final partition sought by the double charge exchange reaction. As one can observe, there are many multi-nucleon transfer paths to be considered in the ^{20}Ne+^{116}Cd $\rightarrow^{20}$O+^{116}Sn transition, which could co-exist and compete with each other as the reaction takes place. In principle, the transfer amplitudes for each of them should be coherently summed to obtain the angular distributions for the final partition. We are just interested in performing multi-nucleon transfer calculations for each path shown in Fig. 2, separately, involving the transfer of nucleons only. Here, it is essential to mention that the paths illustrated in Fig. 2, in which the DCE process can be reached through the one-step direct single charge exchange (direct-SCE) followed by the transfer-SCE or vice-versa, can also compete with the double SCE and the DCE processes driven by mesons exchange [20, 17, 32, 33]. This is because state-of-the-art of this kind of calculations is not yet available. Nevertheless, as shown in Ref. [26], the SCE cross section has the same order of magnitude as the two nucleon transfer reactions leading to the same final partition. So, it might be expected that if two more nucleons are to be transferred after that, the order of magnitude will be the same as the transfer of four nucleons.

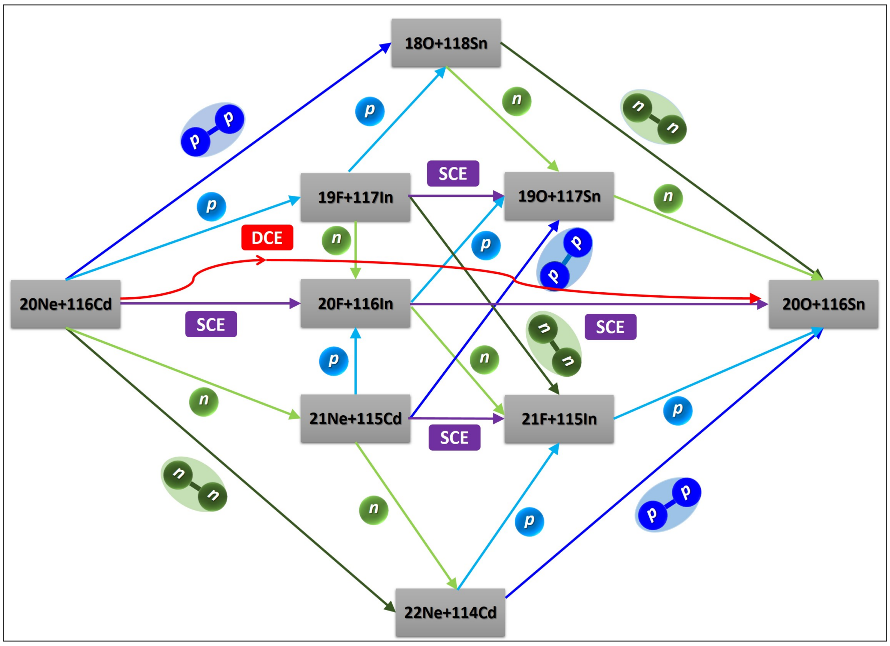

Figure 2. (color online) Scheme of possible transfer reactions that would lead to the same final partition as the direct DCE process driven by meson exchange (represented by a red line). Each reaction mechanism is identified with one color. Notice that the sequential two-proton (two-neutron) transfer is represented by p-p (n-n), while the direct two-proton(two-neutron) transfer is by $2p$ ($2n$).

The coupled reactions equations were solved by considering the DWBA and CCBA approaches. In all partitions the São Paulo potential [34, 35] was considered in the real and imaginary parts of the optical potential with the following strength coefficients $U(R) = (1.0 + 0.78i)V_{LE}^{SP}(R)$ [36, 37] once the couplings with inelastic states into the partition were not regarded. Conversely, the normalization factor 0.6 is used in the imaginary part when the couplings with relevant inelastic channels are explicitly included in the coupled equations scheme [2, 3, 5, 6, 7, 10, 22, 24, 38, 39]. The integrated cross-sections for the final channel $^{20}O_{g.s.}(0^+)+^{116}Sn_{g.s.}(0^+)$ corresponding to each multi-nucleon transfer path were calculated in

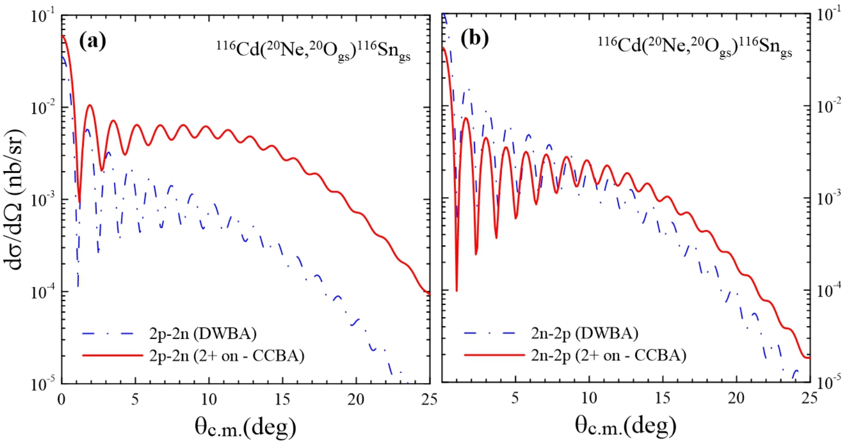

Figure 3. (color online) Theoretical angular distribution for the $^{20}O_{gs}+^{116}Sn_{gs}$ channel corresponding to the paths where the direct two-proton stripping transfer takes place followed by the direct two-neutron pickup reaction and the opposite case, as illustrated in Figs. 1.

Ref. [10]. They were found much lower than the preliminary experimental value, which is some nanobarns. The highest theoretical cross-section was found near 10^{-3} nb (three orders of magnitudes smaller than the experimental value).

To investigate the role played by couplings to the 2_1^+ collective states of both ^{20}Ne and the ^{116}Cd nuclei on the transfer-DCE cross sections, couplings with these inelastic states were explicitly introduced in the coupling scheme. These collective states were accessed by considering the deformation parameters $\beta = 0.72$ [40] and $\beta = 0.135$ [40] for the projectile and target, respectively. The basis of the heavier nuclei states in the intermediate partitions was assumed with eigenstates of energies up to around 2 MeV. The calculations cover a high density of states for these medium-heavy nuclei. In Fig. 3, as an example, the effect caused by the inclusion of the inelastic states couplings in the initial partition is shown. This figure corresponds to the angular distributions for the direct two-proton transfer followed by the direct two-neutron transfer and vice-versa. In addition, as one can observe, the couplings with the 2_1^+ collective states of both ^{20}Ne and the ^{116}Cd nuclei are significant, mainly for the case where the transfer of charged particles initiates the multi-nucleon transfer. On the other hand, the cross section remains too small compared to the experimental data which is in agreement with what was stated in [41] for the case of ^{40}Ca(^{18}O,^{18}Ne)^{40}Ar at 15 MeV/u. These results are a milestone for the NUMEN project [20] once the transfer-DCE process can be considered a weak contaminant of the measured meson-driven DCE cross section.

3. Conclusion

The present work has initially shown the feasibility of the method considered to describe the experimental data corresponding to the transfer of one and two particles, or even one alpha particle. This methodology was employed to determine the cross sections concerning the transfer-DCE process which could be present in the ^{116}Cd(^{20}Ne,^{20}O)^{116}Sn reaction, at 306 MeV incident energy. The experiment was carried out at the INFNLNS, in Catania, with the 20Ne beam accelerated by the K800 Superconducting Cyclotron. This reaction was selected into NUMEN project to measure the double charge exchange cross section on 116Cd, an isotope candidate to observe the $0\nu\beta\beta$ decay.

The role played by the multi-nucleon transfer in the ^{116}Cd(^{20}Ne,^{20}O)^{116}Sn reaction was found irrelevant once the theoretical cross sections associated with each path of Fig. 2 are very small. The highest was three orders of magnitude lower than the estimated data. The DWBA and CCBA approximations were adopted to analyze of the transfer mechanisms. Moreover, the independent coordinates scheme was considered in the direct two-particle transfer. The spectroscopic amplitudes were determined from shell model calculation by using the NUSHELLX code. Besides, the double folding São Paulo potential was considered in the real and imaginary parts of the optical potential of all partitions. This became our methodology of transfer calculations that is parameter-free and has been extensively used in Refs. [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 21, 22, 23, 24, 26].

We also have explored the influence of the couplings of the 2_1^+ collective states of both ^{20}Ne and ^{116}Cd nuclei in the initial partition on the transfer-DCE cross section corresponding to the $^{20}\mathrm{Ne}_{\mathrm{g.s.}}+^{116}\mathrm{Cd}_{\mathrm{g.s.}}$ channel. The inclusion of these couplings did not change the conclusion that the theoretical transfer cross sections were very small in comparison with the experimental data, at least three orders of magnitude lower.

The present results for the transfer-DCE reaction are in agreement with what was stated by Cappuzzelo et al. [41] when proposed a tool toward $0\nu\beta\beta$ nuclear matrix elements analyzing the ^{40}Ca(^{18}O,^{18}Ne)^{40}Ar reaction at 270 MeV, despite the rather qualitative argument in the analysis of the authors. This result is a milestone for the NUMEN project, demonstrating that the meson exchange is actually feeding the measured DCE.

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